Development of a 50mN class hydrogen peroxide monopropellant microthruster for CubeSat applications

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- Microthruster design
- Microthruster fabrication
- Experimental test
- Summary
Introduction
Constellation operations of satellites

Dispenser spacecraft array, Swales aerospace, 1999

RapidEye satellites, German

Small satellites constellations, Skybox for google, 2016
Constellation operations of satellites

CubeSat class nanosatellites sent from the ISS, Nanosatisfi, 2013

NanoRacks Cubesats drifting away from ISS, NASA, 2014

Flock-1 Satellites deployment, NASA, 2014
### Required thrust for nanosatellites operations

<table>
<thead>
<tr>
<th>Mission</th>
<th>Mission Time</th>
<th>Thrusting Time</th>
<th>Δ V (m/s)</th>
<th>Thrust (μ N / kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase altitude from 700 km to 701 km</td>
<td>0.82 hours (half orbit)</td>
<td>10 min</td>
<td>0.53</td>
<td>880</td>
</tr>
<tr>
<td>Boost altitude by 100 km at GEO</td>
<td>1 week (half orbit)</td>
<td>1 week</td>
<td>3.65</td>
<td>6</td>
</tr>
<tr>
<td>Change inclination by 1˚ at 700 km altitude</td>
<td>0.82 hours (half orbit)</td>
<td>10 min</td>
<td>131</td>
<td>220,000</td>
</tr>
<tr>
<td>De-orbit from 700 km (Hohmann transfer)</td>
<td>0.80 hours (half orbit)</td>
<td>10 min</td>
<td>160</td>
<td>270,000</td>
</tr>
<tr>
<td>Change inclination by 1˚ at GEO</td>
<td>12 hours (half orbit)</td>
<td>10 min</td>
<td>54</td>
<td>9,000</td>
</tr>
<tr>
<td>Move 10 km ahead at 700 km altitude</td>
<td>3.3 hours (two orbits)</td>
<td>40 min</td>
<td>1.1</td>
<td>460</td>
</tr>
</tbody>
</table>

For orbit transfer, attitude control, and drag compensation of cubesat class nano satellites, 6 μ N – 270 mN thrust is required

→ Development of small scale thruster is essential

## Propulsion types for microthrusters

- **Microthruster**
  - Thruster for several $\mu$N or mN class thrust generation

<table>
<thead>
<tr>
<th>Type</th>
<th>Reignition</th>
<th>Throttling</th>
<th>System complexity</th>
<th>Specific impulse</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mono propellant</strong></td>
<td>Possible</td>
<td>Possible</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Solid propellant</strong></td>
<td>Impossible</td>
<td>Impossible</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Bi propellant</strong></td>
<td>Possible</td>
<td>Possible</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td><strong>Electrical</strong></td>
<td>Possible</td>
<td>Possible</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td><strong>Cold gas</strong></td>
<td>Possible</td>
<td>Possible</td>
<td>Low</td>
<td>Very low</td>
</tr>
</tbody>
</table>

- Mono-propellant microthruster, An et al., 2006
- Bi-propellant microthruster, Huh et al., 2014
- Solid-propellant microthruster, Lee et al. 2009
Monopropellant alternative

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrazine (N$_2$H$_4$)</td>
<td>High specific impulse / toxic / expensive for handling</td>
</tr>
<tr>
<td>HAN (NH$_3$OHNO$_3$)</td>
<td>Green propellant / detonable / high viscous / need preheating</td>
</tr>
<tr>
<td>ADN (NH$_4$N(NO$_2$)$_3$)</td>
<td>Green propellant / high viscous / need preheating</td>
</tr>
<tr>
<td>Hydrogen peroxide (H$_2$O$_2$)</td>
<td>Green propellant / lower specific impulse / easy decomposition by catalyst</td>
</tr>
</tbody>
</table>

- Hydrogen peroxide is one of the suitable propellant for a microthruster
- Simple system without additional heater installation and high pressure device
- Economical cost for thruster development and testing using green propellant

Experiment with safe gear and without...
Previous work of monopropellant thruster

- Insufficient catalyst durability and propellant decomposition
- Necessity for additional heater installation
- Micro structure failure stemming from thermal stress

* Hitt D L et al. 2001 *Smart Mater Struct* **10** 1163-75
***Sungyong An. 2006* Master’s thesis at KAIST
**Takahashi K et al. 2006* In: *Proc. of the 23rd Sensor Symp.*, pp 513-6
Research objectives

- Fabrication of a micro liquid monopropellant thruster using green propellant;
  - with sufficient catalyst durability and decomposition efficiency
  - considering structural thermal management

- Feasibility testing of use of micro cooling channels in micro scale thruster to deal with thermal stress.

- Effect of micro cooling channels on performance of a micro liquid monopropellant thruster.
Microthruster design
Microthruster design

- **Design procedure**
  - Thruster components (injector, chamber, nozzle), micro cooling channels, and material selection
Microthruster components design

- **Injector**
  - Propellant mass flow determination and spray
  - 10% pressure degradation of chamber pressure for thrust stability
  - Width 50 μm, depth 250 μm, length 500 μm single injector

- **Chamber**
  - Place where propellant decomposition occurs by catalyst
  - Design chamber pressure 2 bar
  - Propellant decomposable catalyst capacity 1.08 g/s cm³
  - Chamber volume 0.065 cm³, height 2.25mm, aspect ratio 1.6
Microthruster components design

- Nozzle
  - Decomposed product acceleration
  - 1D isentropic flow assumption for flow estimation
  - Converging diverging nozzle
  - Contraction angle 45°, expansion angle 12°
  - Nozzle exit Mach number 1.74
  - Nozzle throat area 0.09 mm², nozzle exit area 0.13 mm²
Fabrication material considerations

- Micro fabrication materials for a microthruster

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>125 W/m K</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>25 W/m K</td>
</tr>
<tr>
<td>HTCC</td>
<td>20 W/m K</td>
</tr>
<tr>
<td>LTCC</td>
<td>3 W/m K</td>
</tr>
<tr>
<td>Glass</td>
<td>1 W/m K</td>
</tr>
</tbody>
</table>

- Lowest thermal conductivity with glass
- Advantages of high aspect ratio machinability
- Cost–effectivity, chemical resistance and transparency
Considerations for microthruster design

- Previous work* shows instability of thrust generation stemming from insufficient injector thickness and injector’s inadequate pressure drop
- Horizontal type was selected considering aspect ratio limitation of photosensitive glass fabrication process

### Designed thruster without cooling channels

#### Thruster specification

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Thrust</td>
<td>50 mN</td>
</tr>
<tr>
<td>Chamber pressure</td>
<td>2 bar</td>
</tr>
<tr>
<td>Propellant</td>
<td>90wt% $\text{H}_2\text{O}_2$</td>
</tr>
<tr>
<td>Specific impulse</td>
<td>72 sec</td>
</tr>
<tr>
<td>Propellant flow rate</td>
<td>0.07 g/s</td>
</tr>
<tr>
<td>Catalyst capacity</td>
<td>1.08 g/s/cm$^3$</td>
</tr>
<tr>
<td>Catalyst volume</td>
<td>0.065 cm$^3$</td>
</tr>
<tr>
<td>Catalyst</td>
<td>Pt / Al$_2$O$_3$</td>
</tr>
<tr>
<td>Catalyst support size</td>
<td>40 ~ 45 mesh</td>
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Component layers for the microthruster without cooling channels
Designed thruster with cooling channels

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Microthruster main profile and channel

Component layers for the microthruster
Microthruster fabrication
Microthruster fabrication process

Lithography procedure

1. Quartz wafer
2. 310 nm UV
3. Photosensitive glass
4. Cr Mask
5. UV Exposure
6. Heat Treatment
7. Etching
8. Polishing
9. Bonding
Thruster components with channels

Component layers for the microthruster with channels
Thruster fabrication results

- Optical microscope image

Micro injector fabrication with 100.2% accuracy
Thruster fabrication results

- Optical microscope image

Micro nozzle

Micro nozzle throat fabrication accuracy 90%, nozzle exit 98%
Thruster fabrication results

- Optical microscope image

Micro cooling channel fabrication accuracy 102%
Considerations for catalyst fabrication

- **Catalyst – Platinum**
  - Good performance
  - Melting temperature 2041 K
  - Durable at high temperature and pressure

- **Support – Alumina pellet**
  - High surface mass ratio (~ 255 m²/g)
  - Thermally, physically robust
  - Strong adhesion with metal
  - 40 ~ 45 mesh (425 µm – 325 µm) size γ-alumina
Pt/Al₂O₃ fabrication procedure

1) Before loading
   - Wash 40 – 45 mesh γ-alumina with water
   - Dry at 300 °C for 1 hour

2) Loading active-material
   - Use H₂PtCl₆ 6H₂O as precursor
   - Evaporation method

3) Calcination
   - Evaporate water
   - Eliminate impurities at furnace

4) Reduction
   - With hydrogen gas at high temp
Fabricated catalyst and SEM results

Pt/Al$_2$O$_3$ catalyst (40 – 45 mesh, 355 – 425 µm)

Scanning electron microscopy (SEM) results

Platinum on alumina support
Energy dispersive X-ray spectroscopy (EDS) results of the fabricated catalyst

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt %</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>26.22</td>
<td>47.07</td>
</tr>
<tr>
<td>Al</td>
<td>45.2</td>
<td>48.12</td>
</tr>
<tr>
<td>Pt</td>
<td>27.67</td>
<td>4.07</td>
</tr>
<tr>
<td>Cl</td>
<td>0.91</td>
<td>0.74</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Thruster integration procedure

1. Thermal bonding
2. Sensors installation
3. Catalyst insertion
4. UV bonding

Fabricated Pt/Al₂O₃ catalyst
Thruster fabrication results

Integrated microthruster with micro cooling channels
Component layers for the microthruster without channels
Fabrication result without cooling channels

Integrated microthruster without cooling channels
Experimental test
Experimental setup

Experimental setup for the microthruster test
Experimental test result
Experimental test results with channels

- Micro cooling channel effect occurs
- Chamber temperature 323 °C and pressure 1.9 bar
- Estimated thrust generation 48mN
Experimental test results without channels

- No cooling effect occurs
- Chamber temperature $583 \, ^\circ C$ and pressure 2.2 bar
- Estimated thrust generation 53mN
Test results comparison

- Lower chamber temperature, pressure, and surface temperatures by micro cooling channels
- Estimated thrust generation decreased by 10% with excessive cooling effect
Test results comparison

- Relieved thermal shock by 64% with cooling effect
Summary of test results

<table>
<thead>
<tr>
<th></th>
<th>With channels</th>
<th>Without channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber pressure</td>
<td>1.9 bar</td>
<td>2.2 bar</td>
</tr>
<tr>
<td>Chamber temp</td>
<td>323°C</td>
<td>583°C</td>
</tr>
<tr>
<td>Surface temp</td>
<td>96°C</td>
<td>145°C</td>
</tr>
<tr>
<td>Estimated thrust</td>
<td>48 mN</td>
<td>53 mN</td>
</tr>
<tr>
<td>Pressure rising time</td>
<td>2.5 sec</td>
<td>3.0 sec</td>
</tr>
<tr>
<td>Temp rising time</td>
<td>5.1 sec</td>
<td>3.5 sec</td>
</tr>
<tr>
<td>C* efficiency</td>
<td>26%</td>
<td>31%</td>
</tr>
<tr>
<td>Temp efficiency</td>
<td>58%</td>
<td>84%</td>
</tr>
<tr>
<td>Thermal shock</td>
<td>95 °C /s</td>
<td>283 °C /s</td>
</tr>
</tbody>
</table>

- Relieved thermal stress with micro cooling effect
- Degraded thruster performance
  (chamber pressure, thrust generation, and efficiency)
Summary
Summary

- Two micro liquid monopropellant thruster were successfully fabricated and operated.
  - Thruster fabrication using photosensitive glass MEMS process
  - Pt/Al2O3 catalyst fabrication for propellant decomposition
  - Sufficient propellant decomposition efficiency and thrust generation; 53 and 48 mN

- Practicality of using of micro cooling channels was successfully validated.
  - Decreasing surface temperature contrary to increasing chamber temperature during operation
  - 34% decreased surface temperature with micro cooling channel

- Performance comparison of the microthrusters with cooling channels and without.
  - Thrust degradation of 10% with excessive cooling effect of micro channel
  - Relieved thermal shock by 64%
  - Necessity of trade off between catalyst efficiency and structure cooling for monopropellant applications
Thank you